GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-16-~~644~~ 664 R5929-0A1 — GTRC/~~GIT~~ — DATE 8 / 6 / 85

Project Director: Dr. N.L. Sankar — School/~~Lab~~ AE

Sponsor: Hughes Helicopters Inc. Centinela and Teale Streets
Culver City, CA 90230

Type Agreement: Purchase Order No. 260561 and Standard Agreement Dated 4/11/85

Award Period: From 1/1/85 To 12/31/~~85~~87 (Performance) 12/31/85 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$
Funded:	$ 10,302.00	$ 10,302.00

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: Development of Computer Codes for Analysis of Rotorcraft Aerodynamics
~~A Solution Procedure For Unsteady Compressible Potential Flow Past Practical Rotor Configurations~~

ADMINISTRATIVE DATA — OCA Contact R. Dennis Farmer X4820

1) Sponsor Technical Contact:

Mr. D. Janakiram
Hughes Helicopters, Inc.
Mail Stop 6 C209
Centinela and Teale Streets
Culver City, CA 90230

2) Sponsor Admin/Contractual Matters:

Mr. Al Ewing
Hughes Helicopters, Inc.
Building 12, T50
Centinela and Teale Streets
Culver City, CA 90230
(213) 305-4410

Defense Priority Rating: ______ Military Security Classification: ______
(or) Company/Industrial Proprietary: ______

RESTRICTIONS

See Attached ______ Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with NONE PROPOSED

COMMENTS:

AUG 1985 RECEIVED Research Reports Office

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 3/9/88

Project No. E-16-664 School/~~Lab~~ AE

Includes Subproject No.(s) N/A

Project Director(s) N. L. Sankar GTRC/~~GIT~~

Sponsor McDonnell Douglas Helicopter

Title Development of Computer Codes for Analysis of Rotorcraft Aerodynamics

Effective Completion Date: 12/31/87 (Performance) 12/31/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Copy of Last Invoice Serving as Final
- [ ] Release and Assignment
- [ ] Final Report of Inventions and/or Subcontract: Patent and Subcontract Questionnaire sent to Project Director [ ]
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Continues Project No. ______ Continued by Project No. ______

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Project: E-16-664

IRAD Status Report

Project No. ______________________ Date 4-29-1986

Project Name ______________________ Reporting Period Jan. 1 - March 31, 1986

Responsible Engr Dr. N. L. Sankar Percent Spent ______________________

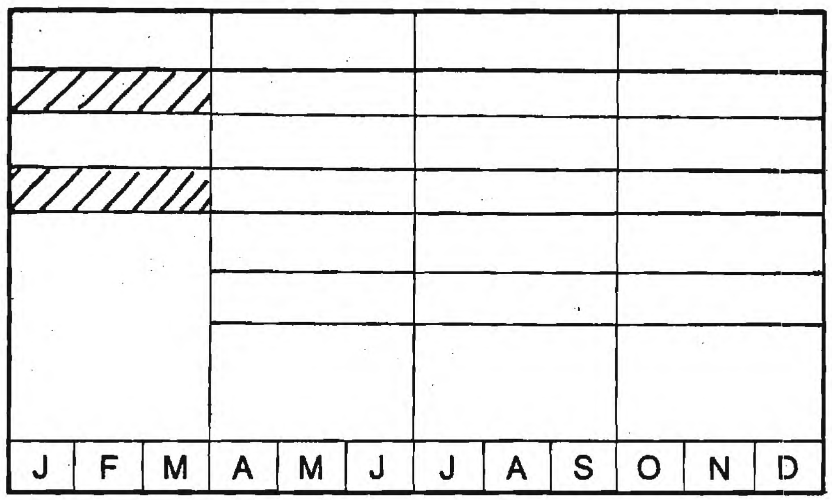
MJO ______________________ Percent Accomplished ______________________

SUMMARY OF PROGRAM OBJECTIVES

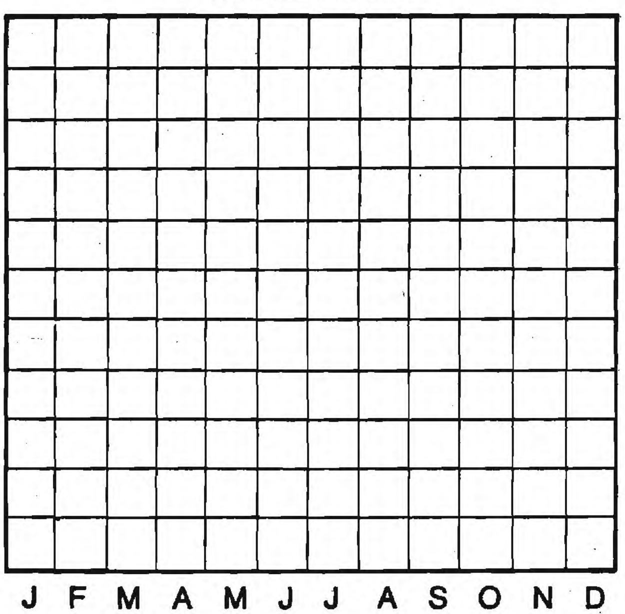
1) Develop a 3-D Flow Solver for predicting the dynamic stall characteristics of airfoils, with a proper account of compressibility, sweep and turbulence. 2) Modify a full potential solver (RFS2) to account for 3-D Blade-Vortex Interaction. 3) Modify this solver to account for weak viscous effects.

SCHEDULE OF TASKS/MILESTONES

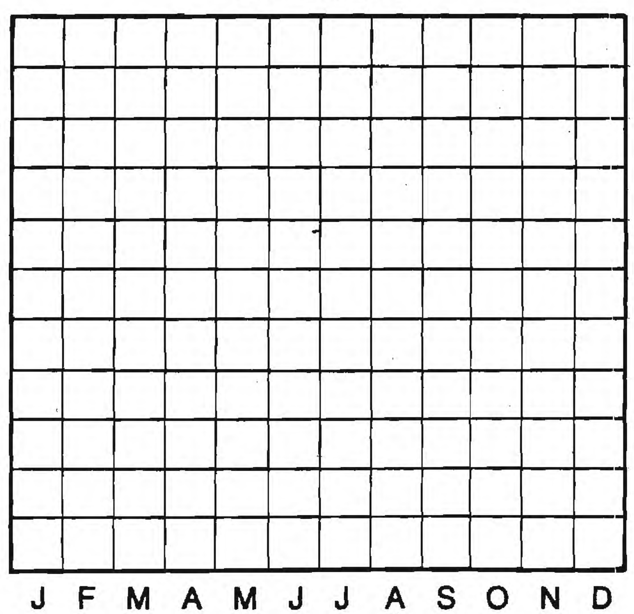
1. 3-D Dynamic Stall Solver
2. 3-D BVI Solver
3. 3-D Boundary Layer Incorporation into RFS2



MANHOURS



DOLLARS



ORM NO. 10340

Hughes Helicopters, Inc.

SUMMARY OF PROGRAM ACCOMPLISHMENTS/PROBLEMS FOR REPORTING PERIOD

1. The dynamic stall solver (called DSS3), which includes the sweep effects, has been coded. It has been validated by comparisons with experiments by Carta, shown in Figures 1 through 4, attached. In Figure 1, the capability of this solver to predict C_L vs α static characteristics is demonstrated. In Figures 2 through 4, the C_L, C_D and C_M stall characteristics, obtained using this solver, are plotted for an unswept blade.

2. The 3-D BVI interaction problem has been formulated, and some of the modifications to the RFS2 solver have been coded.

PROJECTED ACCOMPLISHMENTS/PROBLEMS FOR NEXT REPORTING PERIOD

1. The DSS3 solver will be validated further by computing the dynamic stall characteristics of a 30^{o} sweep rotor blade, and by comparing this data with Carta's experiments.

2. The 3-D BVI solver will be executed for a 3-D BVI problem simulated experimentally by Caradonna and Tung. Surface pressure comparisons will be made with the experiments.

3. The 3-D weak viscous correction procedure will be formulated, and all computer coding relevant to this effort will be completed.

Project E-16-664. April- June 30, 86

Summary of Program Accomplishments/Problems for Reporting Period:

1. The dynamic stall solver DSS3, which can account for blade sweep effects, was used to study the dynamic stall characteristics of a NACA 0012 airfoil at a 30 degree sweep. The free-stream Mach number was 0.3, and the Reynolds number 3.77 Million. The lift, drag and moment characteristics are plotted on figures 1,2 and 3. For comparison, the dynamic stall characteristics of a zero sweep blade for identical flow conditions are plotted on figures 4,5 and 6. The experimental data documented by Carta are plotted on these figures. The following comments are in order, regarding these results:

a. The similarity of the dynamic stall characteristic loops for the 30 degree and zero degree sweep cases indicates that the zero degree sweep results may be scaled to produce the 30 degree sweep data. Such a scaling has been done by the present researchers and the two load loops are virtually identical when the dynamic pressure is properly scaled. The swept blade calculations show a strong radial flow in the entire flow domain, which affect the boundary layer velocity distributions compared to the 2-D case.

The fact that the numerical results at 0 and 30 degree sweep may be collapsed onto a single set of load hysteresis loops lends support to the engineering practice where only the 2-D load data are experimentally obtained, which are then scaled to account for sweep effects.

b. The numerical results do not compare very well with the experimental observations of Carta. Carta predicted a dramatic influence of blade sweep on the dynamic stall loops which are not supported by the present numerical studies. As these discrepancies between the theory and experiments were a surprise to the us, a careful study of the experimental investigation was made. It was found that in the experiments, no transition strip was used and the flow was allowed to transition naturally. Unfortunately natural transition depends on a variety of unknowns such as tunnel conditions, freestream condition etc. and can not be accurately quantified for use in numerical calculations. In our calculations we have assumed the flow to be turbulent everywhere; this in our opinion produces the above discrepancies. We have talked with Dr. Ken McAlister of the U.S. Army Aeroflightdynamics Directorate, who concurs that transition loaction can critically influence the dynamic stall characteristics.

2. The three-dimensional full potential flow solver RFS2 was modified to account for three-dimensional Blade-Vortex interaction phenomenon. The modified flow solver was calibrated by performing a 3-D blade-vortex interaction study for the flow conditions considered by Frank Caradonna et al. Since there is some uncertainty in the measured blade tip Mach number and the strength of the passing vortex, these values were adjusted slightly (Tip Mach number changed from 0.8 to 0.82, vortex strength reduced to 80% of the experimentally measured value). Other 2-D and 3-D studies by previous workers have also used the values quoted above. Good agreement between the experimentally

observed surface pressure distributions and numerical results have been observed throughout the interaction. In figures 7 and 8, the surface pressure predictions at two azimuth locations are compared with experiments.

Projected Accomplishments/Problems for Next Reporting Period:

1. The rigid body blade motions associated with cyclic pitch variation and blade flapping will be directly incorporated into the RFS2 solver. Currently these effects are accounted for as simple angle of attack corrections. The modified solver will be calibrated for a number of flow conditions where experimental data is available.

2. The 3-D blade vortex interaction effort will be extended to strong BVI phenomena where the passing vortices produce significant disturbances on the rotor flow field.

3. The boundary layer schemes incorporated into the RFS2 solver will be calibrated through a number of nonlifting, forward flight studies.

E-16-664

GEORGIA TECH RESEARCH CORPORATION

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0420

Telex: 542507 GTRCOCAATL
Fax: (404) 894-3120

Phone: (404) 894- 4817

Refer to: JG/02.212.000.87.003

January 13, 1987

McDonnell Douglas Helicopter Company
500 East McDowell
Building 530, Mail Stop B346
Mesa, AZ 85205

Attention: Dr. Janaki Ram
Chief Acoustics

Subject: Proposal for "Development of Computer Codes for Analysis of Rotocraft Aerodynamics"

Dear Sir:

Georgia Tech Research Corporation is pleased to submit the enclosed proposal on behalf of Dr. L. N. Sankar of the School of Aerospace Engineering, Georgia Institute of Technology. This proposal is for continuation of the research currently being conducted under MDHC purchase order number HH 260561. We propose that this effort be funded by an revision to that order.

We appreciate the opportunity to submit this proposal. If you have any questions, please call me at 404/894-4817 or Dr. Sankar at 404/894-3014.

Sincerely,

Jerry Goldbaugn
Contracting Officer

JG/sdm

Enclosure: Proposal - two (2) copies

DEVELOPMENT OF COMPUTER CODES

FOR ANALYSIS OF ROTORCRAFT AERODYNAMICS

Research Proposal

Submitted to the

McDonnell Douglas Helicopter Company

by

Georgia Institute of Technology
School of Aerospace Engineering
Atlanta, Georgia 30332

L. N. Sankar, Assoc. Professor
Principal Investigator
(404) 894-3014

W. M. Sangster, Dean
College of Engineering
(404)894-3350

R. B. Gray, Acting Director
School of Aerospace Engineering
(404) 894-3000

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INTRODUCTION

During the past two years, under the support of the McDonnell Douglas Helicopter Company, two flow solvers were developed. The first solver is a compressible Navier-Stokes solver called DSS2 (Dynamic Stall Solver II) capable of handling arbitrary airfoil geometries that are of interest to the designer. This solver may be used to predict the static lift, drag and moment characteristics of airfoils for which experimentally determined load characteristics are not available. It may also be used to determine the dynamic stall hysteresis characteristics of airfoils for a variety of flow conditions. A version of this solver can accurately account for the effects of the yaw angle of the flow relative to the blade leading edge on the airfoil static and unsteady load characteristics. Versions of this solver which can handle two-dimensional blade-vortex interactions have also been developed for the McDonnell Douglas Helicopter Company.

The second solver is a three-dimensional full potential flow solver called RFS2 (Rotor Flow Solver II). This computer code solves the three-dimensional unsteady full potential equation in a body-fitted moving coordinate system, and can be used to predict the airloads over lifting rotor blades in hover or in forward flight. The compressibility effects of the flow around the blade tip on the advancing side, including the formation and propagation of shocks may be analyzed using this solver. This solver has been coupled to the CAMRAD freewake code in a manner which allows this code to provide solutions for user prescribed trim conditions. Since full potential codes can not handle distributed vortex sheets and vortex filaments which exist in the rotor wake, this solver relies on freewake codes such as the CAMRAD code to provide information about the wake, usually in the form of a table comprised of the wake-induced flow angle of attack corrections at a number of azimuth locations. This solver can handle blade motions (cyclic pitch and flap) and unsteady aeroelastic deflections exactly, provided such information is supplied to the solver. A version of this solver capable of handling close blade-vortex interactions also exists.

PROPOSED WORK

During the next year, these two solvers will be further refined, and will be calibrated against available experimental data. Effort will be made to reduce the computer times of these solvers as much as possible. In addition, the capabilities of the RFS2 code will be enhanced in the following areas:

1. Incorporation of Boundary Layer Effects Analysis Capability into RFS2:

Viscous effects play a dominant role in the aerodynamics of modern rotor blades and significantly influence the power requirements. On the advancing side, the adverse pressure gradients generated by shock waves tend to thicken the boundary layer at the foot of the shock, and may even cause a local separation of the flow field. On the retreating side, because of the high angles of attack encountered, a reversed flow region occurs near the blade root, and a partially separated flow occurs near the tip. Over a portion of the blade the flow is massively separated and dynamic stall occurs.

While it is conceded that all these phenomena may be adequately predicted by three-dimensional Navier-Stokes solvers with suitable turbulence models, the routine use of three-dimensional Navier-Stokes solvers in rotorcraft design and analysis is several years away due to the large computing costs associated with the Navier-Stokes simulations. Thus, the rotorcraft designers need an inexpensive but reasonably accurate way of estimating the effects of boundary layers and flow separation on the rotor airloads.

In anticipation of this need for inexpensive viscous correction techniques, a research effort was initiated during the previous reporting period (January 1-December 31, 1986). During this period, a survey of a variety of 2-D and 3-D finite difference and integral boundary layer computation techniques were made, and pilot codes based on some simple 2-D compressible boundary layer schemes were developed. This work identified the 3-D or 2-D unsteady/steady integral boundary layer schemes as the most cost-effective means of predicting boundary layer effects. Integral boundary layer schemes are also more robust than finite difference boundary layer schemes, particularly in the vicinity of the separation line. Integral boundary layer schemes have the ability to march through regions of small separation without a breakdown in the marching process. Since many of the flight conditions, for which the RFS2 code would be used as a predictive tool, would almost certainly involve regions of separated flow it becomes necessary to use integral boundary layer schemes.

During the next year, the Nash-MacDonald integral boundary layer scheme will be incorporated into the RFS2 solver. This scheme computes the boundary layer growth at each individual radial station in a strip theory fashion, and is valid for turbulent flow regimes including regions of mild separation. The Nash-MacDonald integral boundary layer scheme can also adequately model the boundary layer thickening that occurs at the foot of the shock waves. In the laminar regions ahead of the transition line, it is proposed that a Thwaites integral boundary layer scheme with compressibility corrections be used.

A number of test cases where reliable experimental data is available will be used to calibrate the viscous flow solver. These cases will be chosen in cooperation with the researchers at the McDonnell Douglas Helicopter Company.

2. Improved Wake Modeling:

In the RFS2 computer code, the tip vortices and the inner wake emanating from the various blades are presently handled as follows. A separate wake code which uses freewake modeling concepts is used to define a wake geometry. The information about the wake structure is allowed to influence the transonic flow computations through a correction to the local angle of attack at every radial station for a given azimuth angle. A global iteration between the RFS2 code and the freewake code is done in a manner similar to that devised by Chee Tung at the U.S. Army Aeroflightdynamics Directorate, in order to ensure that the loads generated at the rotor disk by the blades (as predicted by the RFS2 code) are consistent with the wake geometry structure, and vice versa.

The angle of attack correction approach becomes inaccurate when the wake vortex filaments are too close to the blade, as may occur during a rapid descent maneuver. The angle of attack correction approach can not properly model the rapid spanwise as well as chordwise variations in pressure associated with the close blade vortex interactions. As a result, this approach can not accurately predict the rapid airloads and the aeroacoustic phenomena associated with such interactions.

To investigate if the wake modeling may be improved, during the past year some studies were carried out in which the close blade-vortex interaction between a NACA 0012 rotor and a straight vortex filament of known strength was analyzed. It was found that the velocity field associated with the blade-vortex interaction may be considered as a nonlinear superposition of a rotational flow field computed using the Biot-Savart law, and an irrotational velocity field computed using a modified form of the full potential equation. The surface pressure distributions associated with the this mathematical model of the velocity field was found to agree favorably with the experimental data taken at the U.S. Army Aeroflightdynamics Directorate by Caradonna and his co-workers.

Based on the above study, it is proposed that the RFS2 code be modified so that it handles at least the first two revolutions of the tip vortex (those portions which cuts through the computational domain) as a close blade vortex interaction. Those vortex filaments which lie outside the computational domain, and those that are more than 720 degree azimuth old would still be treated using the angle of attack correction approach. The RFS2 solver will still continue to rely on a separate freewake code to provide the wake geometry. New modules will be added to the RFS2 code to analyze which portions of these wake elements lie within the computational domain, and to compute the rotational flow field and/or angle of attack corrections associated with the near and far wake filaments respectively. It is believed that it will be necessary to perform this check and perform the costly Biot-Savart velocity calculations only every ten time steps or so (approximately once every 3 degrees of blade rotation). Thus, these additional modules will be expected to increase the cost of the simulations only modestly.

The modified RFS2 solver will be calibrated against available experimental data. Initial code validations will focus on the Cobra OLS rotor, and the three-bladed rotor tested in France. Following these code validations, additional validations will be done in cooperation with the McDonnell Douglas Helicopter Company personnel.

3. Rotor-Airframe Interactions:

The rotor-airframe interaction is one of the least understood areas of rotorcraft aerodynamics. The airframe influences the rotor through upwash induced at the rotor disk due to the presence of the airframe, while the wake shed from the rotor system impinging upon the airframe causes unsteady airloads, vibrations and noise. To this date, no computational tools exist which would model this complex interaction phenomenon.

During the next research period (January 1- December 31, 1987), the rotor-airframe interaction problem will be investigated as follows.

Three computer codes will provide the basis for the rotor airframe interaction. These codes are a) the RFS2 code which can analyze transonic flow over isolated rotors in the absence of other external effects such as airframe induced disturbances, b) a finite-difference full potential flow code developed at the Georgia Institute of Technology by the present investigator which can handle steady and unsteady potential flow around arbitrary fuselage configurations, and c) a freewake code adapted from one of the industry standard flow solvers. The objective is to advance the flowfield around the rotor-airframe-votex structure from one time step to the next. To achieve this, the velocity field is assumed to be made of the following components:

$$V = V_1 + V_2 + V_3$$

where V_1 is the velocity field associated with the rotor field, V_2 is the velocity field associated with the airframe, and V_3 is the velocity field associated with the vortex field. When this superposition is used in the RFS2 code to compute V_1, the other two components are assumed to be known from the previous time level. Likewise, when the component V_2 is computed using the airframe code the components V_1 and V_3 are assumed to be known from the previous time step. The component V_3 may be independently evaluated using the Biot-Savart law. The zero normal velocity boundary condition at all solid surfaces are imposed such that the normal component of the total velocity V is zero at these surfaces. Likewise, when updating the force-free geometry of the wake the entire velocity V will be used to convect the vortex filaments from one location to the next.

It may be shown that the above formulation will lead to a fully consistent rotor-airframe-wake interaction problem. This scheme will be first order accurate in time and second order accurate in space. The mutual interaction between the rotor and the airframe may be accounted for accurately with this approach.

It is proposed that this formulation be implemented as a computer code. Initial code validations will be done for a configuration tested at the Georgia Institute of Technology. Detailed surface pressure measurements at a number of locations on the airframe, as well as flow-visualization studies indicating the vortex structure are available for code validation. Should this interaction study prove useful and economical, it will open the door for additional computations involving practical fuselage geometries. The concepts outlined above can also be used to study main rotor-tail rotor interaction, when the flow fields around the main and tail rotor are both unsteady and/or transonic.

CONCLUDING REMARKS

A one year research effort (January 1 - December 31, 1987) is proposed, incorporating the research tasks discussed above. A budget describing the resources needed to carry out this effort, and the biographical sketch of the principal investigator are also attached.

E-16-664

FINAL REPORT

TITLE OF THE PROJECT: A Solution Procedure for Unsteady Compressible Potential Flow past Practical Rotor Configurations

PERIOD COVERED BY THE REPORT: January 1- December 31, 1985

PROJECT NO: E-16-664 R5929-0A1

SPONSOR: McDonnell Douglas Helicpoter Co.
Attn: Dr. Janakiram
Building 530, M/S B346
McDonnell Douglas Helicopter Co.
5000 E. McDowell Road
Mesa, AZ 85205

PROJECT DIRECTOR: Dr. L. N. Sankar

PROGRESS SUMMARY

During the above period, a three-dimensional unsteady full potential solver was developed. This solver is capable of computing the unsteady, transonic flow around helicopter rotor blades in hover, and in high speed forward flight. The governing equations were cast and solved in a body-fitted coordinate system, allowing the solver to handle advanced rotor configurations, including swept and tapered tip shapes. Standard second order accurate finite difference schemes were used to discretize the governing equations in space. The time derivatives were discretized using first order accurate one-sided differences. This discretization leads to a set of highly coupled nonlinear equations for the velocity potential at every point in the body-fitted coordinate system. Linearization techniques were used at every time step to obtain a system of coupled equations for the velocity potential. Care was taken to ensure that the linearization in time preserves consevation of mass flux across moving shock waves, and that the solution accuracy remains first order in time and second order in space.

When supersonic regions are present, it is necessary to bias the above discretized equations in order that the proper upstream influence will be reflected by the numerical solution. This was accomplished by biasing the density in the upwind direction using a flux biasing technique.

The system of simultaneous equations for the velocity potential, or the change in the velocity potential from one time step to the next, were solved using a Strongly Implicit Procedure. The time marhcing algorithm has been constructed such that this solver may be used as a quasisteady solver, or as a fully unsteady time-accurate solver.

During the above period, this solver was vectorized for efficient performance on the CRAY-XMP computer system. This vectorized version of the solver, known as the RFS2 (Rotor Flow Solver Version 2) code has been supplied to the McDonnell Douglas Helicopter Co. on a magnetic tape, along with a brief user's guide.

The mathematical and numerical details of this solver, and a number of code validation studies have been documented in the public domain (Ref. 1). Recently, the U.S. Army Aeroflightdynamics Directorate personnel have reviewed this solver along with several other codes (Ref. 2).

REFERENCES

1. Sankar, L.N. and Prichard, D., "Solution of Transonic Flow past Rotor Blades Using the Conservative Full Potential Equation," AIAA Paper 85-5012, Presented at the AIAA 3rd Applied Aerodynamics Conference, Colorado Springs, Colarado, October 14-16, 1985.

2. Caradonna, F.X. and Tung, C., "A Review of Current Finite Difference Rotor Flow Methods," Proceedings of the 42nd Annual Forum of the American Helicopter Society, June 2-4, 1986.

E-16-664

DEVELOPMENT OF ADVANCED COMPUTATIONAL TOOLS
FOR
ROTOR AERODYNAMICS

Final Report Submitted to
McDonnell Douglas Helicopter Company

February 1988

Prepared By

Lakshmi N. Sankar
Principal Investigator
School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA

During the period January 1, 1985 - December 31, 1987, under the support of the McDonnell Douglas Helicopter Company research work was done on the development of computer codes that may be used to analyze the aerodynamics of modern high speed rotors in forward flight. As a result of this effort, the following four computer codes were developed.

1. The Rotor Flow Solver (RFS2) Code: This computer code may be used to study the unsteady subsonic and transonic flow past isolated rotor blades of arbitrary planform and shape in hover or in forward flight. This computer code solves the unsteady, compressible, full potential equation in a conservation form on a body-fitted coordinate system, using an efficient time-marching procedure.

2. The Helicopter Fuselage (FUSE1) Code: This computer code solves the steady compressible potential flow over helicopter fuselage configurations through numerical solution of the compressible full potential equation. It may be used to compute the fuselage induced upwash on the rotor blades.

3. The Dynamic Stall Solver (DSS2) Code: This computer code is a derivative of a 2-D computer code developed at Georgia Tech under the support of the U. S. Army Research Office. The basic solver was capable of computing steady, and unsteady compressible viscous flow past arbitray airfoils undergoing small or large amplitude sinusoidal pitching motion. The MDHC version of the code, referred to as the DSS2 code in this report contains numerous enhancements to this basic flow solver, added to increase the solution efficiency and accuracy of the solver. This computer code may by used to generate static airfoil load characteristics, and dynamic stall hysteresis loops of new airfoils for use in rotorcraft performance codes.

4. The Dyamic Stall Solver (DSS3) Code: This flow solver is similar to the DSS2 code, but may be used to compute the dynamic stall

characteristics of airfoils which are at a significant cross flow angle (yaw) relative to the oncoming freestream.

The following sudents at Georgia Tech contributed this project:

1. Devon Prichard, a Graduate Co-Op Student, worked on the development and validation of the RFS2 code and was supported by the McDonnell Douglas Helicpoter Company during the entire duration of this project.

2. Mr. Jiunn-Chi Wu, a Graduate Research Assistant, worked on the development and validation of the DSS2 and DSS3 Solver, and was supported by the McDonnell Douglas Helicopter Company during the period January 1- December 31, 1986.

3. Mr. Neep Hazarika, a Graduate Research Assistant contributed to the development of the fuselage code FUSE1, and was supported by the Georgia Institute of Technology.